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1100 SEVENTEENTH STREET, N.W. WASHINGTON, D.C. 20036

COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE- Direct Radar Determinations of Spacecraft-Planet Ranges on Manned Planetary Missions

TM- 67-1014-8

DATE- December 7, 1967

FILING CASE NO(S)- 720

AUTHOR(S)- H. H. McAdams

FILING SUBJECT(S)- (ASSIGNED BY AUTHOR(S)- Radar Navigation - Planetary

ABSTRACT

On-board radar range-to-planet measurements are shown to be feasible during the encounter phases of manned planetary missions. Hardware necessary for communication with Earth and with planetary probes would satisfy most of the requirements for a radar-ranging system; additional hardware requirements would be minimal. In addition to satisfying terminal guidance requirements not met by other navigational schemes (e.g., navigation based on optical angle measurements or data from the Deep Space Network), the radar measurements would increase the scientific returns of the mission. Radar doppler mapping may be the only technique capable of penetrating the cloud cover to obtain a profile of the planet surface.

(NASA-CR-92790) DIRECT RADAR DETERMINATIONS OF SPACECRAFTPLANET RANGES ON MANNED PLANETARY MISSIONS (Bellcomm, Inc.) 11 p

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FROM: H. H. McAdams

TM-67-1014-8

TECHNICAL MEMORANDUM

Introduction

Self-sufficient navigation on manned interplanetary missions will require the manned vehicle to have the capability of making direct range-to-planet measurements to complement the angular information available from optical measurements. Calculation of range-to-planet from optical angular measurements is possible, but it is unlikely that optical measurements alone will satisfy the requirements of manned encounter missions in the 1970's. In particular, earlier studies[1] have shown that optical navigation will probably not be adequate to inject soft-landing probes into narrow atmospheric entry corridors imposed by structural constraints and targeting requirements.

Estimation of the spacecraft position from planet-planet included angle measurements suffers from the long spacecraft-planet ranges involved so that even small angular errors lead to large positional errors. Estimation of position from measurements of the planet-subtended angle suffers from unfavorable geometry so that small angular errors again lead to large range errors. These problems are compounded by difficulties inherent in angular measurements involving planets. The finite size of the planet together with difficulties in precisely locating the planet limb (particularly for Venus) results in errors in the angular measurements.

The feasibility of direct radar range measurements has generally been discounted. It will be shown here that, on the contrary, radar ranging is a distinct possibility in the vicinity of the planet where direct range measurements are most necessary. The spacecraft radar ranging capability will be estimated by making a parameter tradeoff between the radar equipment expected to be aboard a manned encounter mission in the late 1970's and radar systems that have successfully made planetary range measurements from Earth.

Spacecraft Radar Range Calculation

The radar equation gives the signal power returned from a planet for the case where the entire planetary disk is illuminated by the antenna beam. Thus,

$$P_S = \frac{P_t}{(4\pi)^3} \frac{G^2\lambda^2}{r^4} (\pi R^2) \, g\eta \qquad (1)$$

where

P_t = transmitted power (watts)
G = antenna gain (the same antenna is used for transmitting and receiving) (dB)
λ = wavelength (meters)
r = range to the planet (meters)
R = planet radius (meters)

The product $g\eta$ accounts for the deviations of the actual planet from a perfectly smooth sphere with infinite conductivity. The finite complex dielectric constant of the planet determines η, and the surface roughness is contained in g, the backscatter directivity. For the moon and for Mars at the frequencies of interest here, the product $g\eta$ has been measured to be about .07, while for Venus it is between .10 and .15.[2]

The received noise power is given by $P_N = kT_{eff}B$ where k is Boltzmann's constant, T_{eff} is the effective temperature of the receiving system, and B is the receiver bandwidth. The bandwidth is determined by the doppler spread between the echoes received from the approaching and receding planet limbs. If the receiver bandwidth is less than this spread, the power reflected from the planet limbs is lost, lowering the received power. Since the majority of the returned signal is reflected from a small circular region on the planet surrounding the sub-radar point, making the receiver bandwidth somewhat less than the total doppler spread in the reflected signal will reduce the received noise power more than the received signal power. The available signal-to-noise ratio (S/N) may be increased by several dB in this manner. This point is neglected herein, so that the actual spacecraft radar ranging capability may be somewhat greater than the estimated.

The ratio of received signal power to noise power is

$$\frac{P_S}{P_N} = \frac{P_t}{(4\pi)^3} \frac{G^2\lambda^2}{r^4} \frac{(\pi R^2)\, g\eta}{K\, T_{eff}\, B} \quad . \qquad (2)$$

Equation (2) gives the signal-to-noise power ratio at the receiver output in real time. The final useful signal-to-noise ratio is obtained by digitizing the raw received signal and processing the resulting digital signal to extract the intelligence from deep within the noise. In general, for phase incoherent echoes and additive data processing the signal-to-noise enhancement will be proportional to $n^{1/2}$ where n is the number of echoes included in the sample, while for phase coherent echoes, the enhancement will be proportional to n.[3,4] For rapidly rotating planets such as Mars a broad doppler band must be accepted by the receiver and phase coherency cannot be maintained. For planets rotating more slowly, phase coherency in the returned signal is ultimately limited by the phase-stability of the transmitter. It is assumed here that the echoes returned are phase incoherent. Since n, the number of echoes in the sample, is proportional to t_s, the total tracking time making up the radar sample, the final signal-to-noise ratio after processing is thus proportional to $t_s^{1/2}$.

In Earth-based radar range measurements, integration of several hours of returned signal is often necessary to achieve usable S/N ratios. Use of the spacecraft antenna for such long periods for ranging, particularly as the spacecraft nears the planetary encounter, may not be feasible. It is assumed here that the planet is tracked for a total of only 15 minutes. Since the antenna transmits half of the time and receives half of the time, 30 minutes of antenna time will be required to obtain 15 minutes of returned signal. [The radar range estimation is not sensitive to the particular $t_s(S)$ chosen in Equation (4) below, so that the conclusions of this study are not sensitive to the $t_s(S)$ assumed.]

The relation to be used for comparing the spacecraft and Earth-based radars is

$$S/N \propto \frac{P_t G^2 \lambda^2 R^2 g \eta t_s^{1/2}}{r^4 k T_{eff} B} \qquad (3)$$

Letting E designate Earth-based systems and S designate the spacecraft system, then from Equation (3),

$$\frac{(S/N)_E}{(S/N)_S} = \left(\frac{P_t(E)}{P_t(S)}\right)\left(\frac{G(E)}{G(S)}\right)^2\left(\frac{\lambda(E)}{\lambda(S)}\right)^2\left(\frac{r(S)}{r(E)}\right)^4 \quad X$$

$$\left(\frac{T_{eff}(S)}{T_{eff}(E)}\right)\left(\frac{t_s(E)}{t_s(S)}\right)^{1/2}\left(\frac{B(S)}{B(E)}\right) \qquad (4)$$

Since the Earth-based and spacecraft systems will be compared for measuring the range to the same planet, the product $R^2g\eta$ will be identical for both systems.

As mentioned above, the required receiver bandwidth B is determined by the planet's apparent rotation rate as viewed from the radar site. Thus, B is proportional to the projection on a plane perpendicular to the radar line-of-sight of the vector sum of the sidereal angular velocity of rotation of the planet and the apparent angular velocity due to relative orbital motion. Sidereal periods of Mars and Venus are, respectively, 23.9 hours and 245 days. Within the planet sphere of influence the apparent planet rotation rising from the relative orbital motion is given by r_pV_p/r^2, where r_p is the periapsis radius of the spacecraft orbit, V_p is the periapsis velocity, and r is the instantaneous range of the spacecraft from the planet center. Figure 1 is a plot of the magnitudes of the planet rotation rate and the orbital rotation for three representative missions.

The sidereal rotation of Mars is greater than the apparent rotation from orbital motion when the spacecraft is farther than about an hour from periapsis. Similarly for Venus the sidereal rotation is larger earlier than about 20 hours from periapsis. It will be shown that the radar detection threshold occurs much earlier than these times. Beyond the planet sphere of influence the contribution to the apparent rotation from relative orbital motion will depend upon the particular planet and spacecraft heliocentric orbits. Since the spacecraft is approaching the planet, it is unlikely that the orbital angular rate will be so great as observed on Earth. However, for simplicity, the apparent rotation rates from orbital motion are assumed to be comparable on Earth and on the spacecraft, and the bandwidths of the two radar systems are assumed equal, i.e., B(S)/B(E) = 1.

Table 1 summarizes system parameters as published for two representative Earth-based radar range measurements to Mars and to Venus, together with the radar system postulated to be aboard a manned interplanetary mission. The spacecraft antenna is a 30-foot parabolic dish antenna with gain of 44.6 dB. The effective temperature of the receiving system is taken as 500°K. Quite likely, the effective temperature can be reduced considerably from this value. The average transmitter power is taken to be 300 watts. System losses of 5 dB reduce this to an effective average radiated power of 95 watts. These system parameters are comparable to those that have been proposed in several conceptual designs for manned encounter missions.[5,6]

Note that the antenna and transmitter are required for communication with probes and with Earth. Use of the communication system for ranging imposes no additional hardware requirements on the spacecraft with the possible exception of circuitry to transmit in a pulsed mode and perhaps additional circuitry to detect the returned pulses. The weight penalty for this additional circuitry should be small and acceptable, particularly in view of the gains to be derived from the capability for making direct range measurements.

Figure 2 shows the ratio of $(S/N)_S/(S/N)_E$ calculated from Equation (4) as a function of distance from the planet. The range estimate for the spacecraft radar system is taken as that range at which the spacecraft radar yields an S/N comparable to the Earth-based experiment chosen for comparison (i.e., $(S/N)_E/(S/N)_S = 1$). For Mars the estimated spacecraft radar range is 2.1×10^6 km; for Venus, the estimated range is 6.4×10^6 km. These radar ranges correspond to different times from the planet encounter in different missions. For Mars, the time from mission periapsis at a range of 2.1×10^6 km on three representative missions[7] is:

1975 Mars Encounter	2.8 days
1977 Triple Planet Encounter	5.8 days
1978 Dual Planet Encounter	4.6 days

For typical Venus encounter missions, 6.4×10^6 km corresponds to about ten days before spacecraft periapsis.

Other Considerations

1. Since the spacecraft range and range-rate to the planet change continuously, the positions in time of the returned echoes also change continuously. In Earth-based radar systems the returned signal is heterodyned with a local oscillator whose frequency is changed at a pre-computed rate to effectively cancel the radar-planet relative motion. It is

expected here that, as the spacecraft approaches the planet, the spacecraft orbit will be known well enough to program the spacecraft local oscillator. To some degree a tradeoff exists between the uncertainty in the spacecraft-planet range and range-rate and the amount of data processing required to extract the signal from the noise.

2. The on-board radar range measurements will impose additional requirements on the spacecraft computing system.

3. Direct radar measurements on planetary encounter missions will enhance the scientific return of the encounter mission beyond the navigational benefits. As the spacecraft passes the planet, the spacecraft radar S/N ratio will be well above that available on Earth even in the most favorable circumstances. This will offer the possibility of making detailed radar measurements of the planet surface. For Venus in particular, where the cloud cover may preclude photographic mapping, radar doppler mapping of the planet surface may be possible.

A further possibility is a joint experiment involving the spacecraft transmitter and an Earth-based receiver, or vice versa. This type of experiment would add a new dimension to radar astronomy since the returned echoes would rise from off-normal reflection from the planet surface. In this manner the scattering characteristics of the surface could be determined as a function of angle of incidence and direction of scattering. The sensitive dependence of specular scattering near the Brewster angle on the properties of the near-surface material may be useful for identifying the surface material.[8]

Range Uncertainty

With direct radar range measurements the uncertainty in the range of the spacecraft from the planet center will be reduced to the uncertainty in the distance from the sub-radar point on the planet surface to the planet center. This is determined largely by a lack of knowledge of the planetary radius and shape parameters and to a lesser degree by uncertainty regarding whether the reflections are from the surface or from some sub-surface point. If the planet radius is the major source of range uncertainty, the range could be determined to within $\pm$ 10 km for Mars and to within $\pm$ 50 km for Venus. On a typical mission the accuracy of radar ranging is greater than that estimated to be available either from optical planet-included angle measurements (within $\pm$ 500 km) or from tracking with the Deep Space Network (within $\pm$ 80 km).[1]

Conclusions

On-board radar range-to-planet measurements are feasible during the encounter phases of manned planetary missions. Hardware necessary for communication with Earth and with planetary probes would satisfy most of the requirements for a radar-ranging system; additional hardware requirements would be minimal. In addition to satisfying terminal guidance requirements not met by other navigational schemes (e.g., navigation based on optical angle measurements or data from the Deep Space Network), the radar measurements would increase the scientific returns of the mission. Radar doppler mapping may be the only technique capable of penetrating the Venus cloud cover to obtain a profile of the planet surface.

H. H. McAdams

1014-HHM-ans H. H. McAdams

Attachments
Table I
Figures 1 and 2

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8. Von R. Eshlemann, "Radar Astronomy," Science, 158, 585, 1967.

9. R. M. Goldstein, "Mars: Radar Observations," Science, 150, 1715, 1965.

10. G. H. Pettengill et al, "A Radar Observation of Venus," Astron. J., 67, 181, 1962.

TABLE I

	Mars Exp[a]	Venus Exp[b]	Spacecraft
Antenna Used	Goldstone, JPL	Millstone radar MIT, Lincoln Labs	30-ft parabolic dish
Gain, G (dB)	54.2	37.5	44.6
Wavelength, λ (m)	.125	.681	.125
Effective temperature of receiving system, T_{eff} (°K)	27°	240°	500°
Bandwidth, B (cps)	3700	c	d
System losses, S (dB)	—[e]	-1[e]	-5
Range at time of measurement, r (km)	1×10^8	5×10^7	r(s)
Integration time, t_s (minutes)	400	85	15
Average transmitted power, P_t (watts)	1.0×10^5	1.5×10^5	95[f]

a. See Reference 9.

b. See Reference 10.

c. Not stated.

d. Assumed same for Earth and spacecraft system for identical planets.

e. Included in transmitted power.

f. 300 watts with 5 dB losses = 95 watts effective transmitted power.

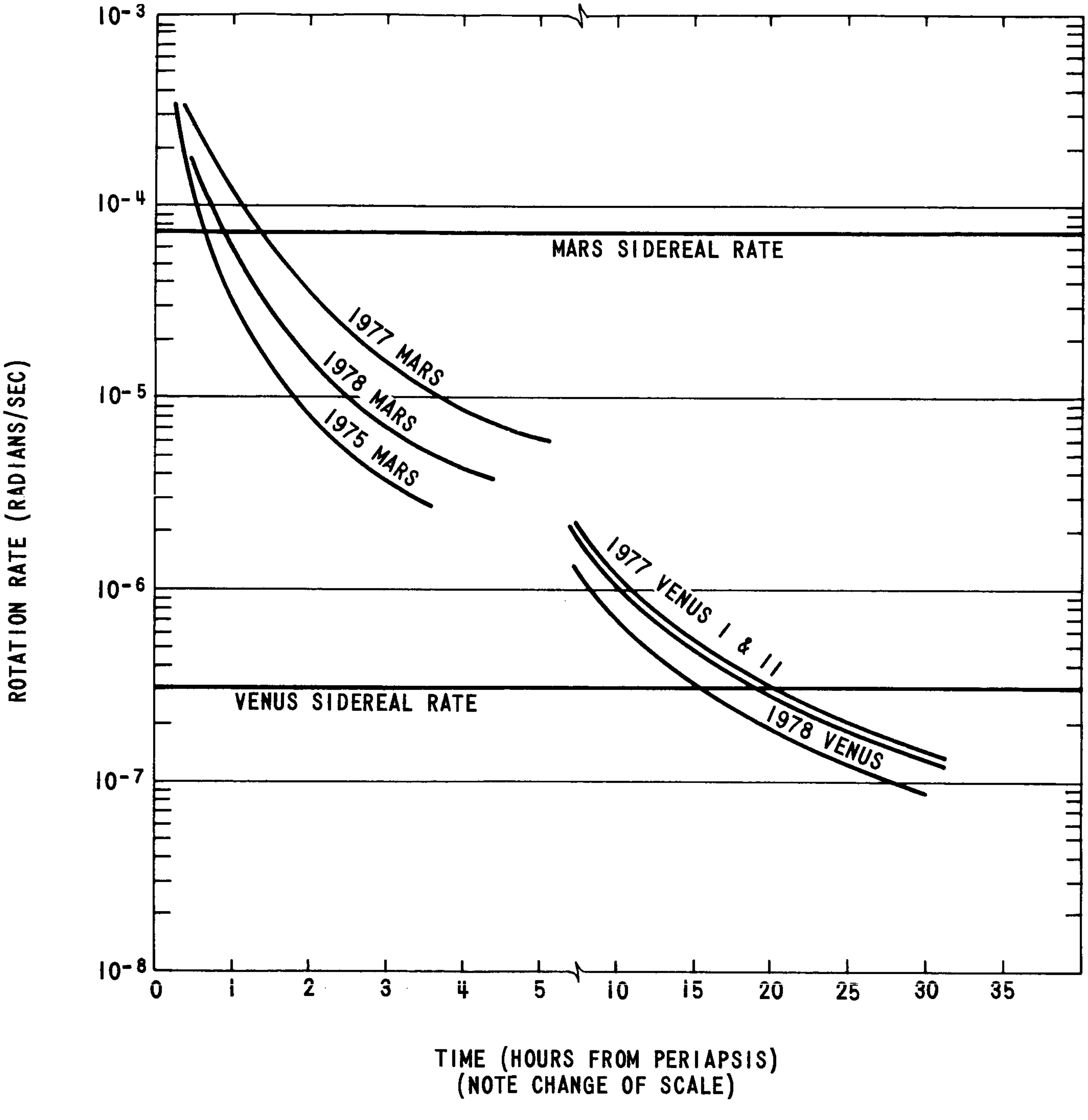

FIGURE 1 - SIDEREAL AND ORBITAL CONTRIBUTIONS TO APPARENT PLANETARY ROTATION RATE

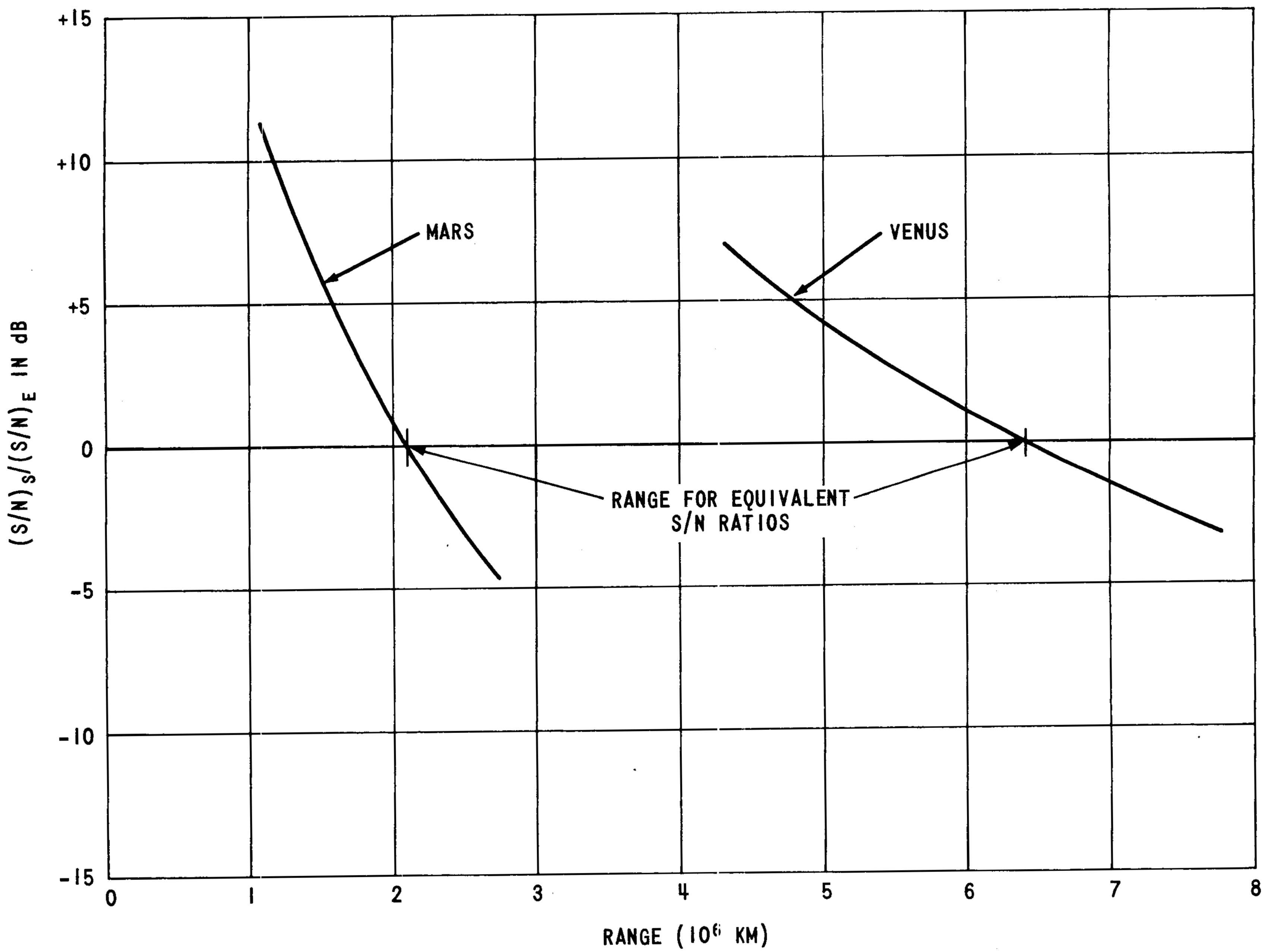

FIGURE 2 - SPACECRAFT RADAR S/N RELATIVE TO EARTH-BASED RADAR